EXPERIMENTAL AND NUMERICAL CHARACTERISATION OF THE OUT-OF-PLANE STRETCH FORMING OF A FIBRE METAL LAMINATE BASED ON A SELF-REINFORCED POLYPROPYLENE COMPOSITE

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Abstract

The numerical simulation of the forming of advanced materials is essential to allow the use of these materials in rapid manufacturing applications. This study uses commercial finite element analysis software and user-defined material properties to accurately simulate the forming of a fibre metal laminate based on a self-reinforced polypropylene composite. Verification of the simulation is achieved by comparison with experimental data obtained using an optical measurement system. Good agreement was found between the numerical results and the experimental data validating the material model used. Friction was identified as a major factor affecting the accuracy of the finite element simulation.

1 Introduction

The reduction in the weight of vehicles is an essential component for reducing demand for non-renewable resources and the greenhouse gas emissions associated with the use of vehicles. Institute for Energy and Environmental Research (IFEU) analysis has shown that fuel savings between 300 to 800 litres over the lifetime of a passenger vehicle can be achieved for every 100kg reduction in mass. This mass reduction also reduces the CO_2-e emissions by approximately nine grams per kilometre. Achieving mass reductions in vehicles has been proposed using two major methods; innovative design, which involves optimising components to achieve better performance from existing materials, and material substitution, where the existing material is replaced by a higher performance material. Primarily, the automotive industry achieves weight reductions through redesigning structures to require lower quantities of steel or substituting steel components with alternative metals with higher specific strengths. Recently, the industry has begun to show interest in material substitution using composite materials. Composite materials can exhibit superior specific stiffness and strength than monolithic metals and have the ability to be tailored to desired applications by adapting the fibre orientation and volume fraction. However, the major obstacle to the use of composite structures in many industries is the high cost and long manufacturing time compared with other materials.

Fibre Metal Laminate (FML) systems are hybrid structures which consist of alternating layers of fibre-reinforced composite materials and metal. Initially, these structures were developed using thermoset matrix composites, the first being ARALL, an aramid fibre reinforced epoxy and the second being GLARE, a glass-fibre reinforced epoxy. Both of these FML systems were developed primarily for aerospace applications, with ARALL being used in the cargo door of the C-17 transport aircraft and the GLARE finding use in the upper fuselage of the Airbus A380. These materials suffer from the manufacturing problems characteristic of thermoset matrix composites, which has led to the investigation of thermoplastic FML systems which can be manufactured in a manner similar to metals.

The most commonly used method for rapidly manufacturing components from sheet metals is stamp forming. This process makes use of a die, blankholder and punch. The die and punch are designed according to the desired final shape and the blankholder is used to control the amount of stretching and drawing of metal into the die. The manufacturing of materials using stamp forming is dependent on having an understanding of the formability of the the material, which is generally determined using the Forming Limit Diagram (FLD) first proposed by Keeler and Backofen [1]. The FLD is used to illustrate the state of strain of the surface of a material undergoing a forming process. The Forming Limit Curve (FLC) is a limit on the FLD which allows the determination of the limiting strains for a sheet material experiencing deformation and is determined for metals through identification of a localised neck in the sheet. Morrow et al. [2] found that composite materials do not exhibit localised necking before failure. The Nakajima method [3], proposes forming specimens of varying width in order to obtain the FLC for all modes of deformation, shown in figure 1.

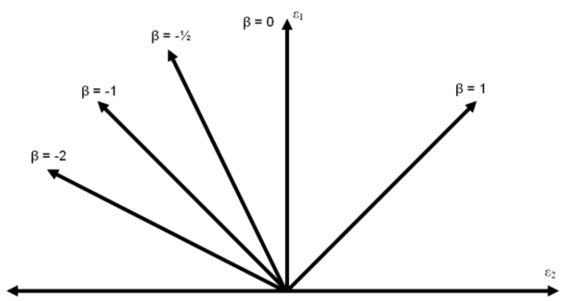


Figure 1. Deformation modes

Currently, there are numerous studies on the forming of composite sheets. However, much of this work considers fabric drapability and the dome forming of composite materials. Cabrera et al. [4] investigated the non-isothermal stamping of all polypropylene and glass fibre polypropylene composites and observed that analysis of the magnitude and direction of the major strain allows the determination of the contribution of intraply shear and fibre drawing. If the major strain is aligned at 45° from the fibres then deformation primarily occurred due to intraply shear, in addition, if the major strain is oriented along the fibres then the sheet was deformed by drawing of the fibres. Breuer and Neitzel [5] found that to reduce wrinkling in the composite sheet the stress should be applied at 45° to the fibre direction to induce shear deformation and the fibres should be allowed to draw into the die. Venkatesan et al. [6, 7, 8] determined that optimal combinations of punch speed, forming temperature and blankholder force allowed composites to exhibit formability comparable to metals.

The modelling of stretch forming for fibre metal laminates requires the development of models for the composite material, the interface between the composite and aluminium and the interaction between the aluminium layers and the press tooling. There are three existing methods for the modelling of FML systems; the micro-level method, which models the individual fibre and matrix interfaces, the meso-level approach, in which the individual plies are modelled as separate homogeneous layers and the macro-level method, which models the homogenised response of the complete laminate [9]. Mosse et al. [10] developed a model for the stamping of a FML into rectangular cups. This study modelled the fibre metal laminate as layers of shell elements bonded by an interfacial friction model. The friction model was development by examining the shear strength of the adhesive using double-lap shear experiments under different normal forces and temperatures. In addition, various studies have investigated the development of FE simulations for assessing the impact response of FML systems [9-14]. These studies again modelled the composite, metal and adhesive layers separately. These models also increased the complexity of the FML models by developing user-defined material models incorporating failure for the composite layer and modelling the adhesive using cohesive elements.

This study uses the techniques developed for the evaluation of formability of metallic materials to develop a finite element simulation, using ABAQUS/Standard, of the forming process for a FML based on a self-reinforced polypropylene composite and an aluminium alloy. The stress-strain behaviour of the constituent materials of the FML were obtained using experimentation and the results were then used to develop the FE model. The experimental evaluation of the formability was performed using three-dimensional photogrammetry and was used to verify the FE simulation of the forming process.

2 Experimental Testing

2.1 Materials and Specimen Preparation

The fibre metal laminates used in this study were created using a combination of a 1.0mm thick self-reinforced polypropylene (SRPP) composite, Curv from Propex Fabrics, and 2 layers of 0.6mm thick 5005-O aluminium. The laminates were manufactured by stacking 230mm by 240mm layers of the aluminium and SRPP in a 2/1 configuration as shown in figure 2. A 50μm thick modified polypropylene (Gluco) adhesive layer was placed between the aluminium and the composite resulting in a nominal laminate thickness of 2.2mm. In order to facilitate a strong bond, the aluminium was etched in a NaOH bath for 5 minutes prior to manufacture and the surfaces of the composite and adhesive were cleaned using isopropyl alcohol. The stacked laminate was then heated to 155°C in a hydraulic press, maintained at this temperature for 5 min at a pressure of 1MPa and then rapidly water cooled.

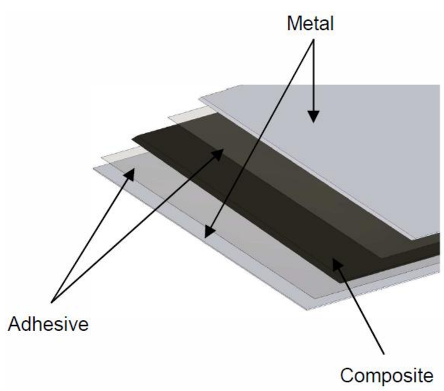


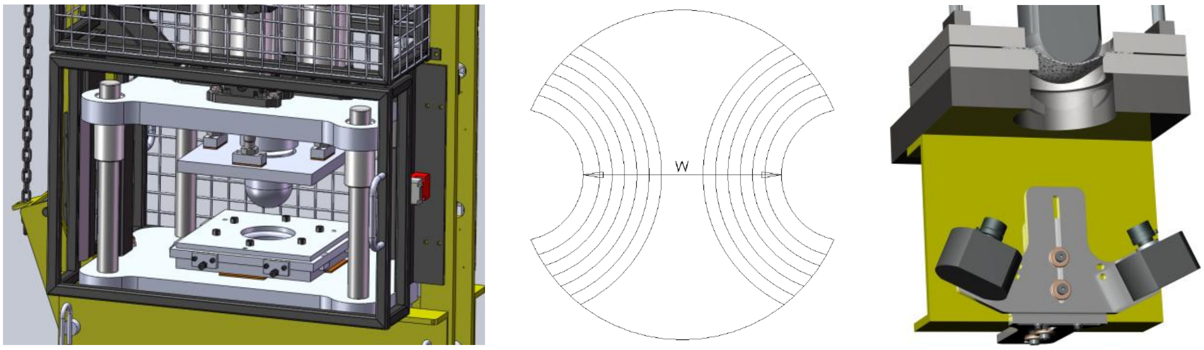
Figure 2. Laminate stacking configuration

2.2 Material Characterisation

Tensile experiments were performed on both the aluminium and the SRPP to obtain the stress-strain relationship, tensile strength and strain to failure. These tests were carried out on straight edge rectangular specimens for the SRPP and dogbone specimens for the aluminium. The specimens were prepared in accordance with the ASTM standards D3039 for the SRPP and A370 for the aluminium. The SRPP tensile tests were performed at a constant crosshead displacement rate of 5mm/min using an Instron 1342 testing machine and the aluminium specimens were tested at a rate of 2mm/min on an Instron 4505 testing machine.

2.3 Stretch Forming Experiments

A custom designed 300kN stamp press with a 100mm diameter hemispherical punch and 105mm open die was used to experimentally evaluate the forming of the FML. A local data acquisition PC controls the feed rate and punch displacement. A compression load cell measured the punch force and a linear potentiometer provided the punch displacement. The experiments were conducted at a feed rate of 10mm/s and the depth at failure was determined by a 2% drop from maximum load. A universal lubricant was used to reduce friction between the punch and the samples. The configuration of the stamp press is shown in figure 3a.



(a) (b) (c)

Figure 3. Experimental setup

A total of 7 geometries, shown in figure 3b, were created to elucidate all deformation modes. These geometries have a varying amount of material removed to provide specimen widths (W) of 25, 40, 55, 70, 85, 100 and 120mm. An open die configuration was used in order to facilitate measurement of the surface strain on the specimens using the ARAMIS three-dimensional strain measuring system, shown in figure 3c. This system assigns a pixel to every point on the surface of the material and is calibrated to observe a volume with an accuracy of 0.02 pixels. This allows accurate observation of the full field strain distribution and the evolution of strain throughout the forming process. To ensure that the ARAMIS system is able to record and calculate strain, each specimen was painted with a high contrast stochastic pattern.

3 Finite Element Model

3.1 Simulation Procedure

ABAQUS/Standard was used to simulate the forming of the FML system. The tools, comprised of the punch, blankholder and die are modelled as 3D analytical rigid surfaces. The aluminium and composite are modelled as three layers of shell elements meshed using S4R elements with reduced order of integration and a large-strain formulation [15]. Individual shell layers were used so that the material characteristics of the SRPP composite and the aluminium could be accurately represented. A typical meshing of the finite element model is illustrated in figure 4a. The interaction between the aluminium and composite layers was developed based on the work of Mosse et al. [10]. This model uses a friction based interaction, with no separation, which exhibits a very high friction coefficient at low temperatures to approximate a strong bond between the layers.

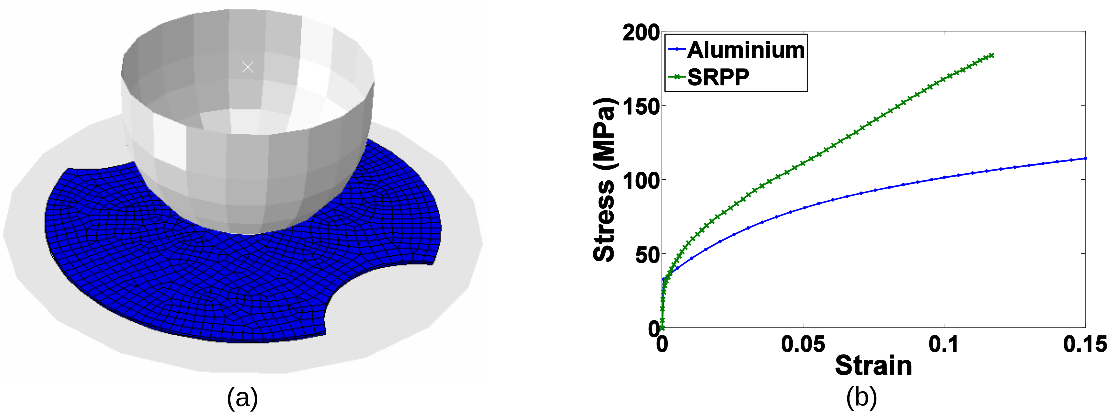


Figure 4. Finite element model (a) and the stress-strain relationship for the materials (b)

The effect of the lock ring, which is used to secure the specimens in the experimental work, is simulated by fixing the outer edge of the shell elements along the centre line of the lock ring.

3.2 Constitutive Model

The constitutive models of both the aluminium and the SRPP were determined by assessing the experimentally determined stress/strain relationship. These relationships are shown in figure 4b. The material behaviour for the aluminium was modelled using elastic-plastic behaviour in ABAQUS/Standard. This model uses the initial elastic response of the material and value for stress at certain values for plastic strain.

The model for the SRPP was developed using a user-defined material subroutine (UMAT) implementing the tangent modulus method. This method uses the stress/strain relationship of the material, shown in figure 4b, to define the instantaneous modulus of the material. After the experimental determination of the stress/strain relationship a two-part non-linear curve was used to model the behaviour of the material. Equation 1 describes the stress/strain behaviour for the SRPP in the region $0 < \varepsilon < 0.04$ and equation 2 describes the subsequent behaviour. The modulus is determined by taking the first derivative of these equations.

$$\sigma = y_0 + A_1 e^{\frac{-\varepsilon}{t_1}} + A_2 e^{\frac{-\varepsilon}{t_2}} \tag{1}$$

$$\sigma = A + B\varepsilon + C\varepsilon^2 \tag{2}$$

The parameters for these equations are given in table 1.

Parameter	Value
y_0	245.582
A_1	-35.213
t_1	0.00205
A_2	-200.841
t_2	0.13898
A	30.942
B	-6388.032
C	1827.998

Table 1. Constitutive model parameters

4 Effect of lock ring on surface strain

The application of blankholder force is performed before the specimen is formed. However, due to the nature of the lock ring, the specimen experiences a "pre-stretch" prior to forming. The effect of this phenomenon was analysed by obtaining an image of every specimen prior to securing the lock ring. These images showed the specimens in equilibrium and allowed the calculation of the effect of the lock ring on the surface strain by comparison to an image taken immediately after the application of blankholder force.

Figure 7a shows the results of the strain calculations for the effect of the lock ring on the experimental geometries. All geometries experienced approximately the same effect by the lock ring. It can be seen that the lock ring applies a small positive increase in major strain and a generally negative increase in minor strain. The strain ratio for the "pre-stretch" is approximately 0.3 with the larger blanks such as the 100mmHG and the 120mmHG experiencing some regions of biaxial stretch. The main reason for obtaining this information is to accurately simulate the lock ring by means of a "pre-stretch" in the finite element model in addition to the fixed edge. The pre-stretch was applied in the simulation by applying a small displacement to the outer edges, shown in figure 7c, which corresponds to the surface strain behaviour obtained through experimentation. The magnitude of the force was dependant on the geometry being examined and the force applied by the blankholder. The blankholder force, and therefore the amount of "pre-stretch" experienced by the specimen, was controlled by a torque applied to six bolts positioned outside the lock ring. The results of the pre-stretch condition applied to the finite element simulation are shown in figure 7b. The results for the "pre-stretch" in the FE simulation show that the applied force is an appropriate method for simulating the effect of the lock ring on the experimental specimens.

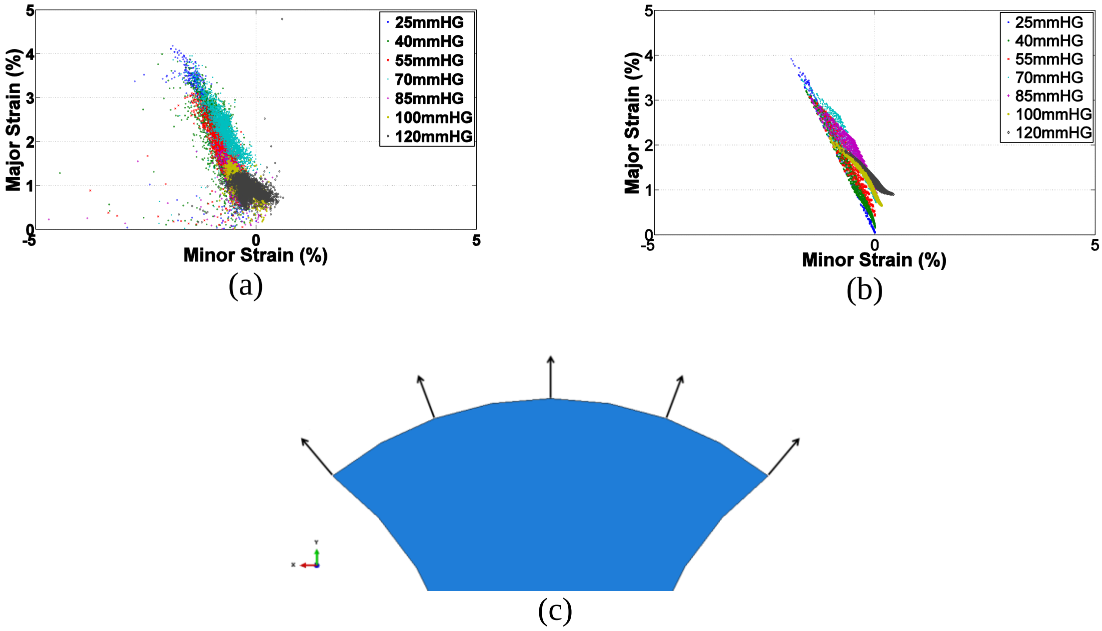


Figure 7. Effect of the lock ring on the surface strain of the experimental specimens

5 Forming limit diagram

The ARAMIS strain measurement system allows the capturing of images at a rate of 20 images per second, therefore, the surface strain distribution for each specimen was obtained for every 0.5mm of forming depth. In order to facilitate rapid comparison to the finite element model, the surface strain at a depth of 15mm was chosen since this depth is prior to any failure in the laminate [16].

Figure 8a shows the forming limit diagrams for all of the experimental geometries at a forming depth of 15mm. Figure 8b shows the results from the FE simulation of the specimens. It can be seen that the FE results compare well with the experimental results and that the models exhibit the same deformation behaviour. It can be seen from figures 8a and 8b that the FE simulation of the 100mmHG and 120mmHG specimens display slightly more positive values of minor strain compared to the experimental specimens. This phenomenon was found to be caused by the value of friction between the tools and the specimen in the model. High friction between the blankholder, die and specimen results in increased values for the minor strain for corresponding values of major strain. This is due to the high blankholder and die friction increasing the lateral constraint in the specimen and therefore increasing the biaxial stretch component of the strain. The effect of friction at the punch operates in the opposite manner to the blankholder and die, with high friction at the punch leading to reduced values of both major and minor strain and low friction leading to more biaxial stretch conditions. These results agree with the effect of friction predicted by Martin et al. [17].

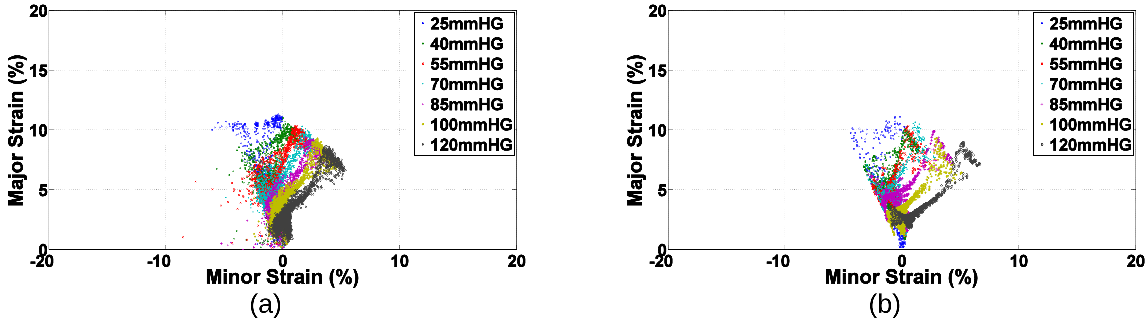


Figure 8. Forming limit diagrams for the experimental geometries (a) and the finite element simulation (b)

6 Effect of geometry on deformation behaviour

Figure 9 shows the evolution of strain and the strain ratio at the pole of the experimental specimens. These results illustrate the applicability of the Nakajima method to FML systems to allow the determination of the forming limit in a similar manner to metals. The figure shows that by varying the specimen geometry, all deformation modes ranging from uniaxial tension to biaxial stretch can be obtained. This is a significant finding for FML systems as it provides a simple technique for determining the forming limits for this class of material system.

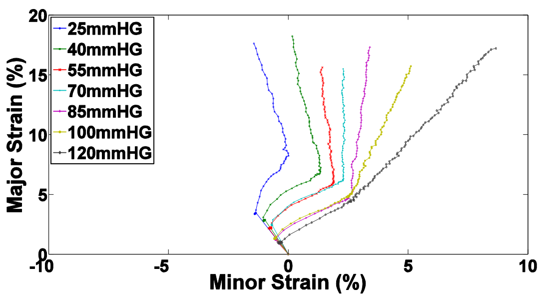


Figure 9. Strain ratio at the pole for the experimental specimens

7 Conclusions and Future Work

This work shows that a finite element model can be used to determine the formability of fibre metal laminates. It shows the importance of correctly defining all of the conditions including material properties, interaction effects and the influence of process variables such as the lock ring and friction. The effect of friction between the tools and the specimens in the FE simulation was shown to have a significant effect on the results, with low friction between the punch and the specimen resulting in incorrect values for the strain ratio and high values of friction lead to reduced levels of major strain.

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